licensing under subpart B, C, D, or E of this part. Authority is also provided for the transmission of voice and/or non-voice messages relating to objects being located.

(b) The use of F1D, F2D, F3E, F9W, G1D, G2D, G3E or P0N emissions is authorized for operation of transmitters in AVM systems.

(c) Frequencies for AVM operations are assignable as follows:

(1) Only wideband pulse-ranging systems requiring 8 MHz bandwidth will be authorized in the 904-912 MHz or 918-926 MHz band segments. AVM operations in these segments are subject to the following conditions:

(i) Notwithstanding the provisions of § 90.173, each of the 8 MHz AVM segments (904-912 MHz or 918-926 MHz) shall be authorized for exclusive use within a 50-mile radius from the geographic center of the urbanized area to be served. The geographic center coordinates shall be determined by using Table 1 of § 90.635. Outside the urbanized areas, the 50-mile radius shall be measured using center coordinates designated by the applicant for the service area.

(ii) An applicant for an AVM system shall not be authorized within 110 miles of the geographic center of an existing or already applied-for wideband 8 MHz AVM authorized on the same frequency segment, unless all affected licensees have agreed in writing to the proposed system.

(iii) Licensees operating in the band 904-912 MHz shall operate their forward link in the range 924.890-925.140 MHz and licensees operating in the range 918-926 MHz shall operate their forward link in the range 904.375-904.625 MHz. Licensees or applicants in the same service area shall coordinate their use of these frequencies in order to avoid interference.

(iv) An entity granted an authorization prior to [effective date of new rules] or licensed for operation in one of the 8 MHz segments (904-912 MHz or 918-926 MHz) in ten or more markets must complete construction [alternative language suggested]

<u>Alternative A</u> -- in all markets within 10 years.

Alternative B -- according to the following schedule:

In at least 10 percent of such markets within 2 years;
In at least 40 percent of such markets within 4 years;
In at least 60 percent of such markets within 6 years;
and in all markets within 10 years.

Authorization for those stations not in compliance with these construction requirements shall cancel automatically.

(v) Authorizations granted under the interim rules prior to [effective date of new rules], including their successors or assignees in business, will be permitted to be renewed indefinitely.

(vi) AVM operations will not cause interference to government stations which operate in these bands and can tolerate interference from industrial, scientific, and medical (ISM) devices and from government stations which operate in these bands.

(2) AVM operations in the 903-927 MHz band, other than wideband pulse-ranging systems, shall be authorized in the 903-904 or 926-927 MHz bands on a regular basis.

(3) Applicants requiring not more than 25 kHz bandwidth per frequency in the 25-50 MHz, 150-170 MHz, and 450-512 MHz bands may either utilize base-mobile frequencies presently assigned the applicant, or be assigned base-mobile frequencies available in the service in which eligibility has been established, provided that:

(i) For transmission between objects and base stations, each frequency in a single-frequency mode of operation will provide location data for approximately 200 objects, or both frequencies in a 2-frequency mode of operation will provide location data for approximately 400 objects, except that for frequencies in the 450-512 MHz band that are assigned in pairs in accordance with the allocation plan for the band, the requirement is that location data be provided for approximately 200 objects for each frequency pair; and a showing is made that 50 percent of the objects will be in operation within the system by the end of the second year of the initial licensed term, and 70 percent will be in operation within the system by the end of the initial licensed term; except that if these loading standards will not be met, frequencies will be assigned only on a secondary non-interference basis to any authorized radiotelephony operation.

(ii) The minimum separation between a proposed AVM station and the nearest co-channel base station of another licensee operating a voice system is 75 miles (120 km) for a single frequency mode of operation or 35 miles (56 km) for a 2-frequency mode of operation. Where the minimum mileage separation cannot be achieved, agreement to the use of F1D, F2D, G1D, G2D or P0N emission must be received from all existing co-channel licensees using voice emissions within the applicable mileage limits. If there is interference with voice operations and required agreement was not received, or operation was authorized on a secondary non-interference basis, the licensee of the AVM is responsible for eliminating the interference.

(iii) Frequencies additional to any assigned under paragraph (i) of this paragraph (c)(3) will not be assigned to the same licensee in the same geographic area until each of such licensee's frequencies for AVM operation is shown to accommodate not less than 90 percent of the frequency loading requirements specified in paragraph (i) of this paragraph (c)(3).

(d) AVM stations are exempted from the identification requirements of § 90.425.

13. Section 90.425 is amended by revising paragraph (d)(5) to read as follows:

§ 90.425 Station identification.

* * * * *

(d) * * *

(5) It is used solely in connection with an Automatic Vehicle Monitoring (AVM) system governed by § 90.239.

* * * * *

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IMPACT OF CO-CHANNEL INTERFERENCE ON 900 MHz WIDEBAND PULSE-RANGING AVM SYSTEM PERFORMANCE

April 6, 1992

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IMPACT OF CO-CHANNEL INTERFERENCE ON 900 MHz WIDEBAND PULSE-RANGING AVM SYSTEM PERFORMANCE

1 INTRODUCTION

The following discussion shows that multiple wideband AVM systems cannot provide reliable service without a co-channel separation requirement. We proceed in three steps. First, we look at the consumer needs for AVM services. We identify the technological attributes (accuracy, coverage, etc.) of an AVM system that serves consumers well. Second, we examine how co-channel interference affects those technical attributes. Finally, we offer our conclusions about the effects of such interference.

2 CONSUMER NEEDS

AVM systems such as Teletrac are focused primarily on the consumer and metro-based business applications. These customers need a system that is both low-cost and accurate, with coverage areas that encompass primarily the greater metropolitan areas where the vehicles are operated. However, interference from a co-channel transmitter would degrade accuracy, coverage, and capacity of the AVM systems such as Teletrac's, and would increase costs to subscribers.

2.1 Accuracy

Co-channel interference would seriously impair the accuracy of Teletrac's vehicle location system. Consumer applications such as stolen vehicle recovery and roadside assistance along with fleet applications such as school bus and transit systems require accuracy sufficient to satisfy a variety of operational needs. These needs include determining the location of a vehicle on a particular street. Police officers need to determine when a stolen vehicle has been hidden in a particular structure, such as a garage. Even if the vehicle has not been hidden, Teletrac's accurate location information dramatically reduces law enforcement and emergency response time since it guides a response team close enough to see the vehicle. Teletrac's 100 to 150 feet of accuracy,[1] combined with highly accurate digitized computer maps fulfill these operational needs.

Accuracy is critical to actually finding the vehicle when a responding agency, such as a police officer or ambulance, arrives at the location provided by an AVM service. Teletrac's accuracy delivers a small search area such as a street intersection. Increasing the location error by 100 feet could require searching two or three residential streets. Even such a small increase in the error would require searching over an area that is approximately four times larger than required with current system accuracy (since the search area varies inversely with the square of the location accuracy). Searching over this larger area adds a great deal of time, especially if the vehicle is not parked on the roadway. The person responding to the service request must then search all possible structures and alleys on every possible street. At some point, the search becomes too difficult, and the AVM system becomes useless for this application.

Section 3 shows that co-channel interference from other AVM systems will degrade location accuracy far below the requirements of the applications described above and will therefore limit the usefulness of the AVM service provided by Teletrac and other AVM system operators.

2.2 Dependability

Customers want their service to be available at all times and everywhere within the coverage area. When customers <u>need</u> service, they need it where they are and right at that moment.

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[1] Teletrac's system provides two operating modes: standard (150 foot error) and high-precision (100 foot error). High-precision is used primarily for stolen vehicle locations.

Dependability can be divided into equipment reliability issues and radio channel availability issues. Teletrac deals with the equipment issue through the use of highly reliable hardware in the vehicle units and the fixed network. Additionally, Teletrac has parallel redundancy in the fixed network.

Regarding channel availability, Teletrac has designed its system to provide rapid response time and reliable radio coverage over large geographic areas. Co-channel interference, however, would degrade availability and thereby limit or destroy system effectiveness. Depending upon the form of the interference, its effects could range from service delays throughout the system to serious degradation of service in part or all of the service area.

The repetition rate and duty cycle of interfering signals can vary widely, depending on whether the interferer is a pulsed periodic, long duration or continuous duty signal. Consequently, we have not tried to model the effects of interference on the time availability of our service in the presence of a co-channel AVM system. However, as shown in Section 4 below, we have modeled the impact of interference on the system coverage area, and we show that co-channel separation is required to assure a level of geographic coverage acceptable to customers.

2.3 Capacity

Fleet tracking applications account for most of the location requests in an AVM system because regular location updates are expected for most units. Consumer applications (stolen cars and emergency assistance), however, are expected to account for most of the usable addresses for location units even though they place lower traffic requirements on the system.

To fulfill these requirements, the Teletrac system has been designed to support millions of addresses and to service over 4,000 location requests per minute. This high throughput is dependent on 100 percent channel availability. Whenever the channel becomes unavailable, synchronization is lost and must be re-established, requiring significant set-up time.

2.4 Affordability

It is generally recognized that a mass communications network with a large number of user terminals should be designed to minimize the cost of the user terminals, even if this means that the fixed network is complex and expensive. For example, very small aperture terminal (VSAT) satellite networks are designed this way, with a complex expensive hub system that communicates with many inexpensive subscriber terminals. For this same reason, the Teletrac system is designed with inexpensive radio location units and a complex fixed network that is shared among all of its customers.

In the presence of interference, however, that fixed network would become drastically more expensive because the number of fixed stations would have to be increased substantially to overcome, if possible,[2] the interference. The result would be that the fixed costs shared among all of Teletrac's customers would increase. If this happened, the overall network design concept of inexpensive radio location units for the consumer would be called into question.

Vehicle location unit that operates on Teletrac's system sell today for about $600. This price is expected to fall as production volumes increase. The Teletrac fixed network costs are covered by a low monthly charge for service. These prices are consistent with the cost of

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[2] As we show later, there are technological constraints which limit the benefits of additional receive sites. See Section 3.3 below.

sophisticated automobile alarms. In the United States two thirds of automobile alarms sell for less than $500. A highly complex vehicle location unit, engineered to overcome co-channel interference problems, would be far more expensive. Its price would be beyond the willingness or ability of many consumers to pay. Similarly, a redesigned fixed network, with more fixed sites, would result in a much higher monthly service charge, and this also would make the service unaffordable to many consumers.

It is then of primary importance to all AVM system operators that co-channel separation requirements be implemented to preserve service quality and thereby allow AVM system operators to deliver maximum value to the public at an affordable price for the consumer.

3 INTERFERENCE EFFECTS ON ACCURACY

In this section, we consider the effects of co-channel interference, such as would be generated by a second AVM system operating in the same band, on the operation of a wideband VLS system and show that such interference seriously degrades the accuracy of the first system.

The technology model used in this example is that of a generic time-of-arrival position location system similar to that used by Teletrac. We believe that the results presented below are broadly applicable to any system that uses time-of-arrival multilateration techniques with mobile transmitters (or systems that are mathematically equivalent to such systems).

The discussion below proceeds in several steps. First, we define the assumed technology. Second, we discuss possible performance measures and explain our choice of a specific measure (the added dispersion of location estimates due to such interference). Third, we discuss the modeling technique we use to calculate our results. Fourth, we present our analysis and results.

Fifth, we describe real-world factors that cause interference effects to be even more severe than predicted by our model. Finally, we offer our conclusions.

3.1 Technological Assumptions

We assume that a time-of-arrival multilateration-based vehicle location system (TOA VLS) is used. To determine the location of a vehicle in such a system, the vehicle transmits a wideband pulse. The time-of-arrival of that pulse at several receiving stations is then measured as shown in Figure 1. This time-of-arrival must be measured with extreme accuracy and precision if the system is to be able to estimate vehicle locations accurately. If we ignore any multipath effects, we see that the difference in the time-of-arrival of the pulse at each base station is directly proportional to the difference in distance to the two base stations. So each pair of receive stations determines a line-of-position,[3] the set of locations where a transmitter would generate the time difference actually seen by the pair of receivers. Figure 2 illustrates three such lines-of-position as would occur in the configuration shown in Figure 1. As can be seen in this example, the lines-of-position all converge. Noise corrupts the TOA measurements and the lines-of-position are really "bands-of-position," that reflect the probable location of the vehicle. And the intersection, instead of being a mathematical point, is a region. This is illustrated in Figure 3 which shows how the neat intersection of Figure 2 becomes an area as noise enters into the analysis.

Notice that the computations in TOA VLS system are conceptually quite similar to those in a navigation system such as LORAN-C or GPS. The major difference in the TOA VLS system is that the signals travel from the mobile to the base and the calculations are performed

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[3] This "line" is typically curved, since it is hyperbolic.

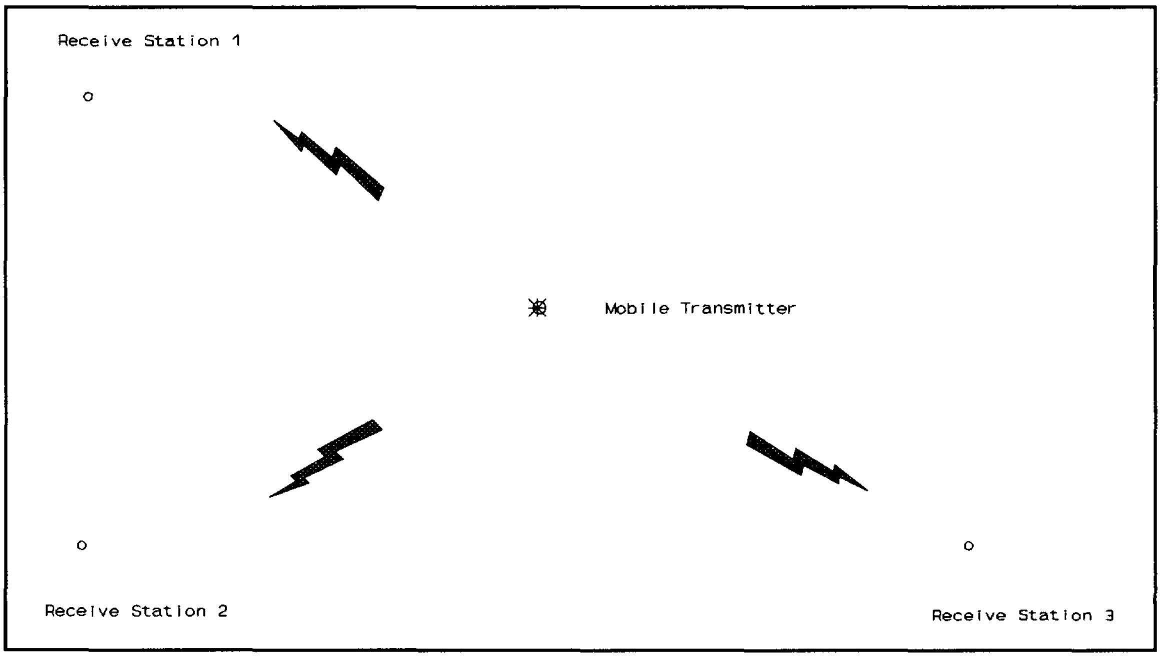

Figure 1 Mobile and Multiple Receive Sites

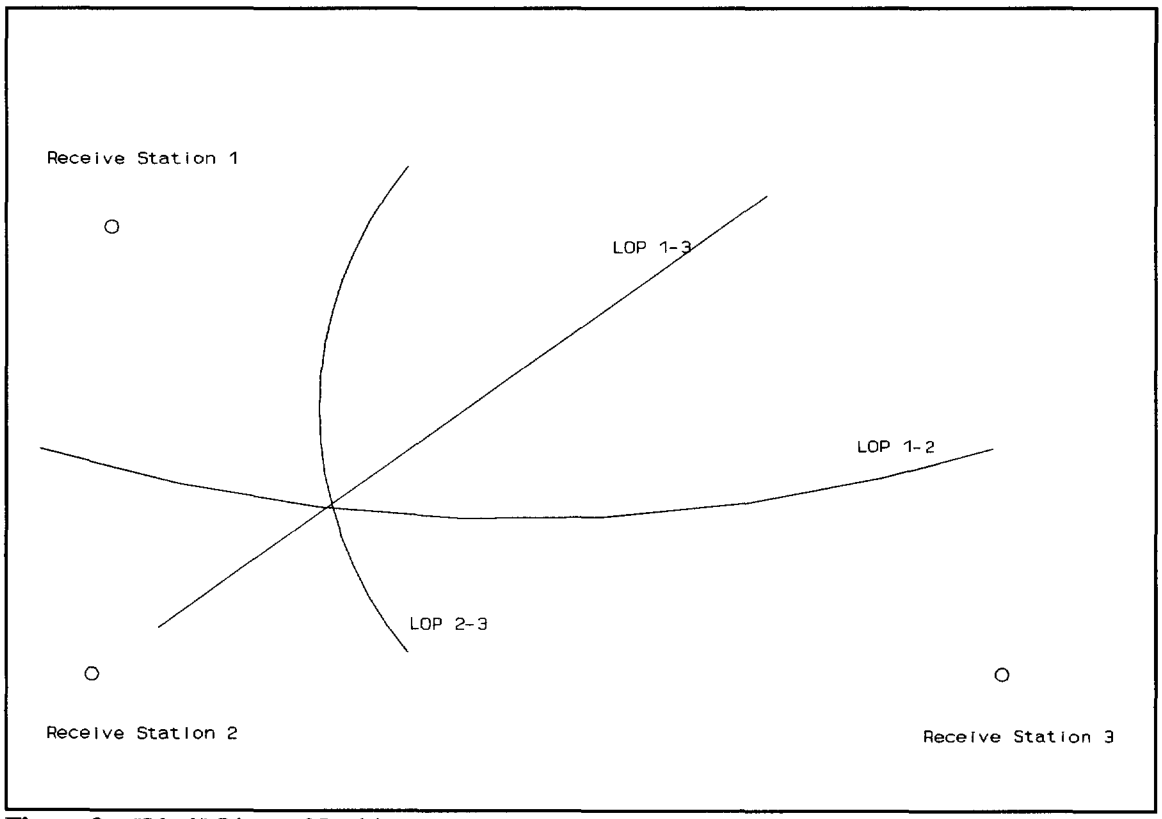

Figure 2 "Ideal" Lines-of-Position (LOP)

at the system control center, not the mobile. Since the calculations are performed at the system control center, vehicle location information is available to dispatchers without further radio communication.

In practice, a real TOA VLS system would use at least four and typically, significantly more than four receive sites in order to improve the quality of the location estimate and to improve reliability. The additional receive sites are needed to cope with the problems caused by location ambiguity (for only three sites), multipath, intermittent noise or interference sources in the band, and the possibility of equipment failure.

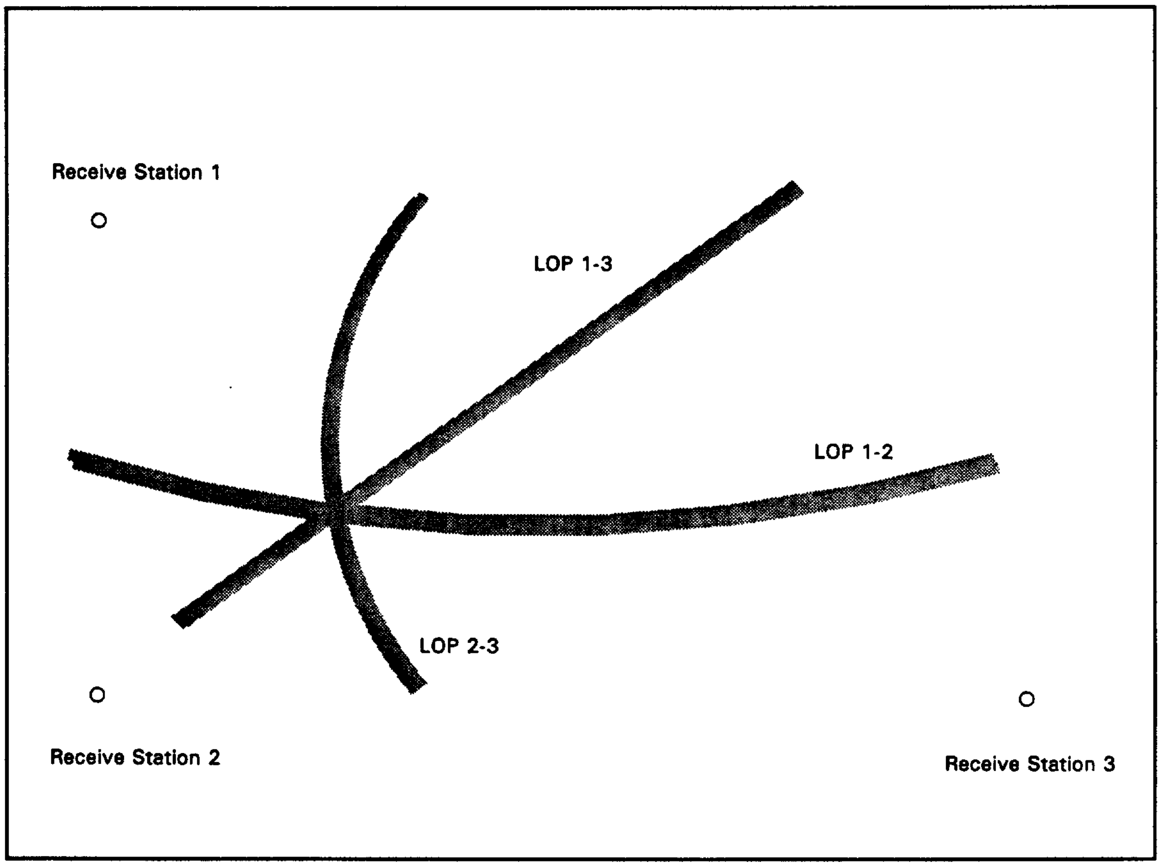

Figure 3 Lines-of-Position Corrupted by Noise

Notice also that any simple measure of interference effects, such as a single site's signal-to-noise-and-interference-ratio (SNIR), is not appropriate for understanding the harm caused by interference. For example, poor SNIR at a single site causes less location error than poor SNIR at many or all sites. In practice, a minimum of four receive sites is required to remove ambiguity associated with the "corrupted lines-of-position" described earlier.

3.2 Measures of Accuracy

As discussed above, the distance errors in the location estimates provided by an AVM system are good measures of a system's performance. Other measures, such as signal-to-noise ratios at receive sites or average signal-to-interferer levels, while easily calculated, do not directly translate into measures of system performance. Location estimates are not perfect, rather errors can occur due to system noise, multipath effects and other departures from an ideal system.

In any particular situation, a statistical description of the errors (the probability density function for the errors) is a complete measure of the quality of the location information. But, the full specification of this distribution is complex and it is hard to communicate or comprehend. As in many other areas of engineering, instead of using the full distribution, statistical measures such as the mean or variance are used.

Typical statistical measures of the quality of location estimates are quantities developed either through the mathematical modeling of system performance or the measurement of system performance. One such measure would be the probability that a location estimate is in error by more than 100 feet. Another measure would be the variance of the distance and between the location estimate and the actual location. A third measure is the circular error probable (CEP). The CEP is the radius of a circle drawn about the estimated location that has a 50 percent probability of including the actual location. This is equivalent to the median of the distribution of the distance between the actual location and the estimated location. A fourth measure would be the 95th percentile of the distribution of location errors. The system operator can effectively "guarantee" (at least with 95 percent confidence) that the location estimate will be within "X" feet of the true location, where "X" is the 95th percentile point.[4]

In our analysis below, we use the 95th percentile point for the additional error created by interference as our measure, since this is an easily understood but robust statistical measure of the dispersion of location estimates about the actual location. This measure corresponds to the actual performance users care about. And, it has the advantage of being reasonably easily calculated in the simulation model.

3.3 Modeling Impairment of Accuracy

Calculation of the 95th percentile point in an interference scenario is a complex process. It depends upon the quality of the time estimates at each station that receives the pulse from the mobile unit. The basic calculation requires the following steps:

- Specify the location of the receive sites, the location of the vehicle and the power and location of the interfering transmitter;
- Calculate the strength of the desired signal at each receive site;
- Calculate the strength of the interfering signal at each receive site;
- Calculate the signal-to-interference ratio at each receive site;
- Simulate the TOA measurement error;
- Taking into account geometric effects, calculate the error in a location estimate;

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[4] We note that the use of a 95 percent criterion in such applications has long standing use. For example, the Mitre Corporation report, *Overview of Automatic Vehicle Monitoring Systems*, August 1973, (NTIS PB-223 509), uses three criteria to compare the operation of AVM systems: the 95 percent point, coverage in the service area, and mean location error. In this study we will use coverage and the 95 percent point.

- Repeat the above two steps thousands of times to generate a group or distribution of location errors; and
- Calculate the 95 percentile point from this distribution.

Teletrac has developed computer models[5] that combine radio propagation modeling with simulation of the estimation of a vehicle location. These computer models allows us to estimate the accuracy of location in a variety of interference scenarios.

We consider a generic receiving system located on flat terrain consisting of four receivers located on the corners of a square 10 miles on a side. The mobile unit is located at the center of the square in the middle of the service area. Figure 4 illustrates this configuration. The interfering transmitter is located about a mile and a third (7,000 feet) from one of the receive sites.

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[5] Today, computer models are a primary tool for designing communication systems. For an overview of their use, see the discussion in *Communications Receivers: Principles and Design*, by Rhode and Bucher, McGraw-Hill, 1988. See also the "Special Issue of Computer-Aided Modeling, Analysis, And Design of Communications Systems" of the *IEEE Journal on Selected Areas in Communications*, Vol. SAC-2, No. 1, January 1984. The editors of that issue give a good explanation of the need for such modeling:

> Performance evaluation and tradeoff analysis are the central issues in the design of communication links and networks. Unfortunately, except for some idealized and often oversimplified cases, it is extremely difficult to evaluate the performance of a complex communication network in closed form using analytical techniques alone...Indeed, there are many situations where explicit performance evaluation defies analysis and meaningful results can be obtained only through either actual prototype hardware evaluation or digital computer simulation. The former approach is generally cumbersome, expensive, time consuming and relatively inflexible. These are considerations which typically weight heavily in favor of computer simulation.

In this model we have chosen a single, moderate, case to illustrate accuracy performance in the presence of increasing interference power levels. In a later analysis we will show the system-wide impact of interference based on Teletrac's minimum accuracy threshold of 150 feet that consumers demand.

While the use of a single location prevents us from exploring directly the effects of the receiver/mobile location geometry on the location estimates in the presence of interference, we should provide some background observations. Any TOA VLS system is limited by geometry.

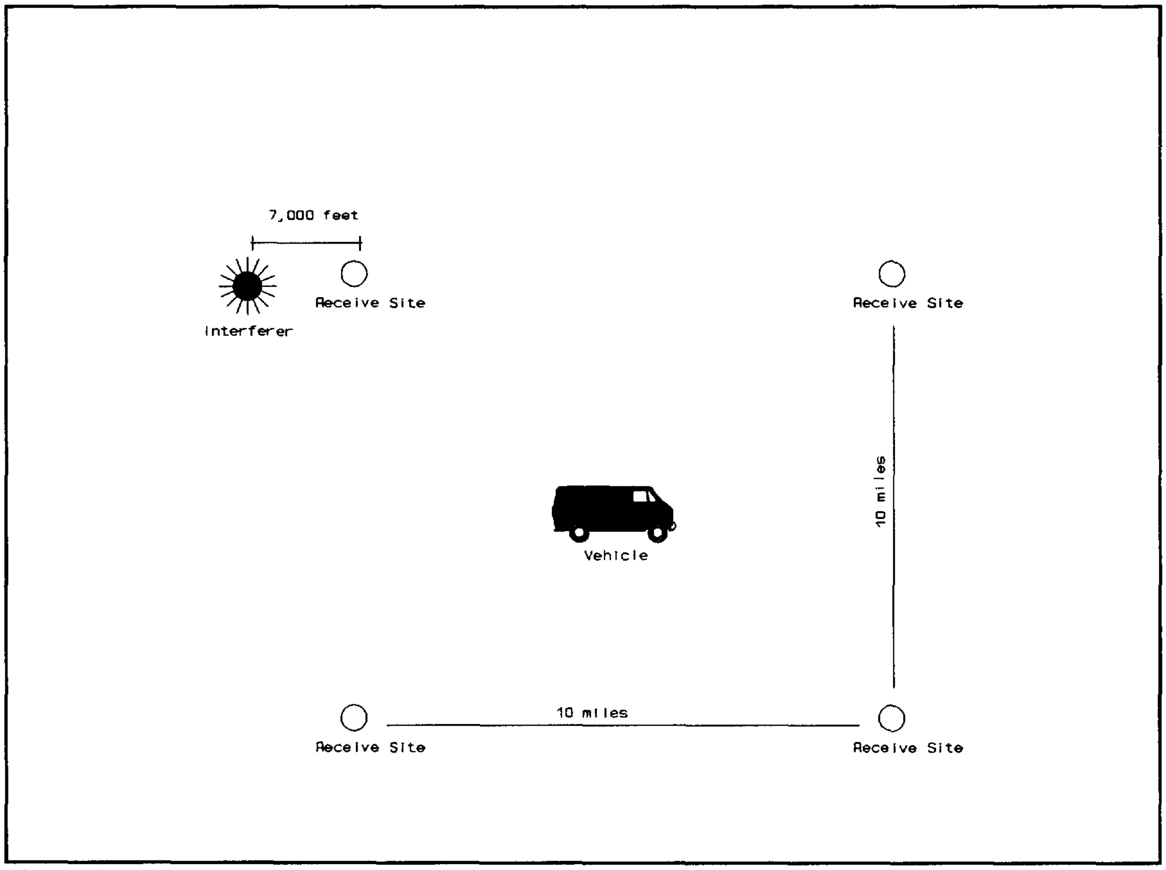

Figure 4 Configuration for Simulation Study of Accuracy Impairment

The phenomenon is called "geometric dilution of precision" (GDOP). Roughly put, in our model it means that, all other things being equal, the farther the actual location is from the center of the square, the greater the location error because the lines-of-position become more parallel. Figure 5 illustrates the magnification of errors through GDOP. The particular case considered above has the most favorable GDOP. Our system coverage analysis in Section 4, below, takes into account adverse GDOP.

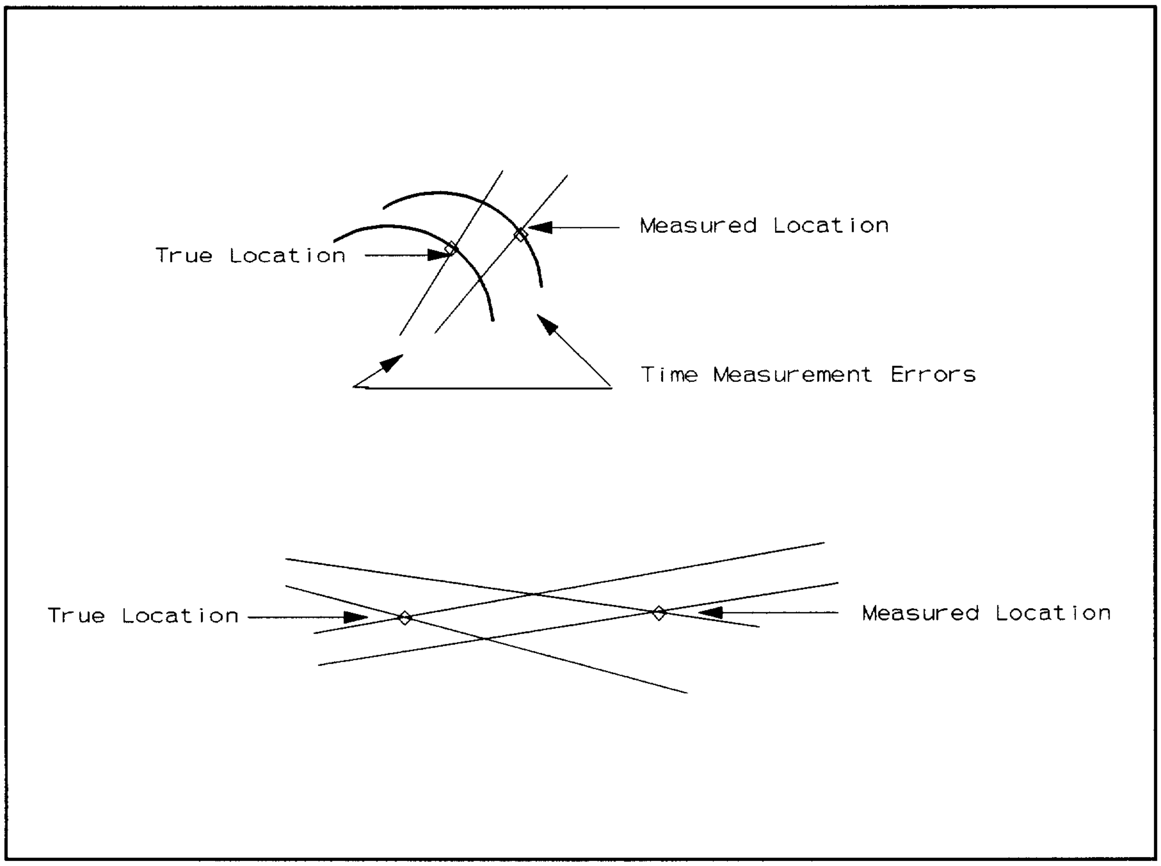

Figure 5 Magnification of Errors Through Geometric Dilution of Precision

3.4 Simulation Parameters and Predicted Loss of Accuracy in Location Estimation

We assume that the mobile unit transmits with 5 watts power and an omni-directional antenna with an antenna gain of -6 dB[6] and transmits a wideband pulse. We assume an r^4 attenuation law for transmissions from both the mobile and the interferer.[7]

We assume that the interfering unit transmits at a given power between 0.1 watts and 20 watts with an antenna gain of 0 dB. These power levels are permitted under both the current rules and the rules we propose today. They are consistent with vehicle location systems using designs different from those of Petitioner, such as systems employing moderate-power fixed transmitters. They are also consistent with a design similar to Petitioner's but using an external antenna with gain.

We assume that the interfering signal is additive white Gaussian noise (AWGN) in the passband of the AVM system receiver. While the assumption of AWGN is widely used in communications engineering because it is both reasonable and mathematically tractable, it may be the case that a deterministic interfering signal degrades performance somewhat more or less than is predicted for a AWGN interference source of the same power.

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[6] This low gain, -6 dB, represents the top end of the range of antenna gains observed with the hidden antennas used in the stolen car service.

[7] The r^4 law is frequently used to model radio propagation in the urban multipath environment. See, for example, *Microwave Mobile Communications*, William C. Jakes, Jr., John Wiley, p. 98. See also, R. C. Bernhardt, "User Access in Portable Radio Systems in a Co-Channel Interference Environment," *IEEE Journal on Selected Areas in Communications*, Vol. 7, No. 1, January 1989, pp. 49-58 and W.C.Y. Lee, *Mobile Communications Engineering*, McGraw-Hill, 1982, pp. 107-108.

Our simulation model then predicts the 95th percentile of the location estimates. The results are shown in the two graphs below. Figure 6 and Figure 7 show the same data plotted with different scales.

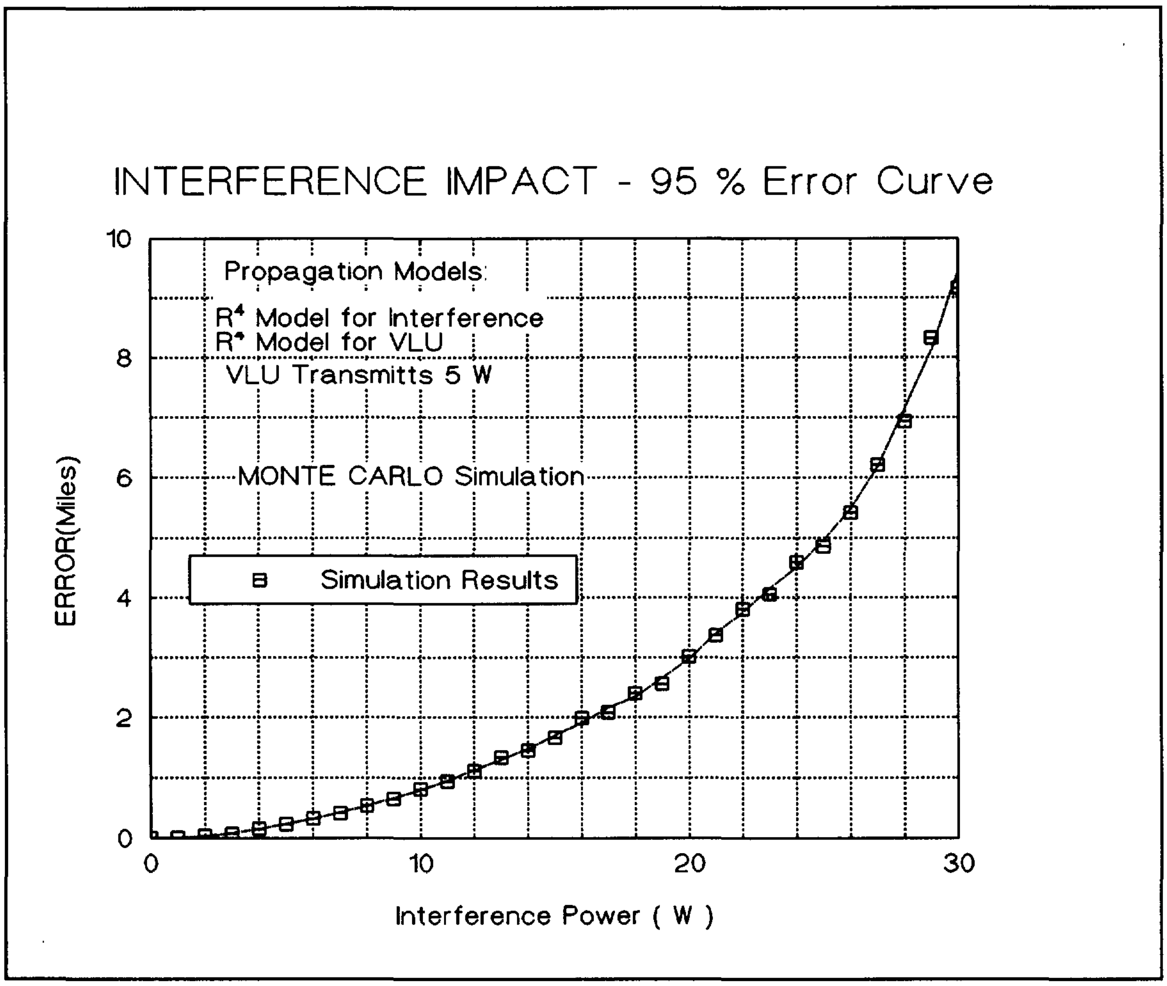

Figure 6 Interference Impact on Accuracy - 95% Error Curve

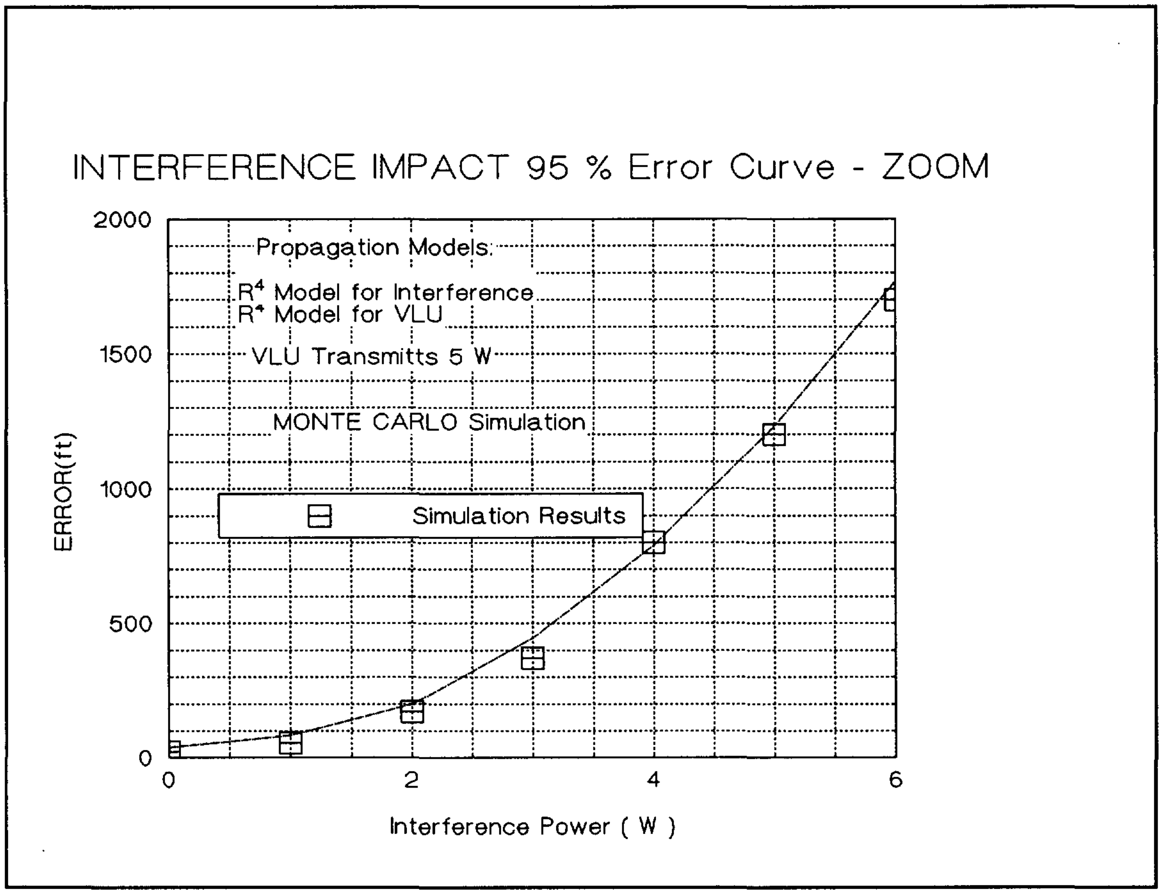

Figure 7 Interference Impact on Accuracy - 95% Error Curve - Zoom

At an interfering power of 10 watts, the 95th percentile of the radial distance error in the location estimate is almost a mile. Raising the interfering power to 30 watts drives the 95th percentile point out to almost 10 miles.

Figure 7 zooms in on the data shown in Figure 6. As you can see, for relatively low interfering powers, say, less than one watt, the added impairment is less than 100 feet. However, as the interfering power increases, the error grows rapidly. At five watts the 95th percentile[8] point is over 1,000 feet.

In the case we have chosen (the car is in the middle of the square of receivers) the system geometry is maximally favorable. The interference case we have considered is in many ways among the most benign. Besides favorable GDOP, the interference is strongest at only one site and is at ground level. An interfering transmitter located on a hill or the top of a building could have a line-of-sight path to all sites which could lead to more severe interference.

3.5 Possible Remedies for Such Interference

After seeing these results one is naturally prompted to ask, "Is there an easy way to engineer around such interference?" The usual communications engineering solutions to radio interference are higher power, directional antennas or separating the interfering and interfered-with systems in frequency.

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[8] While we have not displayed other measures of error, the mean and median errors typically lie in the range 0.35 to 0.6 of the 95th percentile error depending upon the geometry. If the error distance were Rayleigh distributed, then the median error would be approximately one half the 95th percentile point.

Four engineering "solutions" to these interference problems immediately suggest themselves. One is to increase the number of receive sites and thereby increase the probability that there is a nearby receive site that is relatively interference-free. A second "solution" raises the power of the transmitted pulse to allow more accurate measurement of its time-of-arrival. A third approach is to make the pulse longer in time and thereby give the pulse more energy. A fourth approach would be to reduce interference by using directional antennas or steerable null antennas at the receive sites.

Implementing the first solution, increasing the number of receive sites, faces four problems. First, it is expensive. Cutting the separation of the receive sites in half would quadruple the number of sites required. Each receive site requires dedicated equipment, space rental, electric power, and a telephone private line connection. These facilities are not cheap. A proliferation of receive sites substantially increases system cost. Second, and more important, as shown below, multiple receive sites cannot protect against very high power interference sources which would blanket an area and cannot protect against interference sources located near the vehicle being monitored. Third, the problem of geometric dilution of precision is more severe near receive sites. Consequently, multiplying sites can have the unintended consequence of compromising location accuracy. Fourth, it is difficult to find good sites in many areas; zoning, aesthetic considerations and lack of suitable structures or electrical power all limit the number of possible sites.

The second solution, increasing the power of the transmitted pulse, is similarly problematic. Simply raising the transmitted power at the vehicle is technologically and economically infeasible. The current generation of mobile units operate at about five watts. Raising this power 10 to 20 dB (to 50 watts or 500 watts) would create substantial problems with the availability of